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ELECTROMAGNETIC FIELD EXPOSURE IN BROADCAST ENVIRONMENTS

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Summary

Recently there has been renewed concern over possible deleterious health effects from exposure to electromagnetic fields. In the light of increasing evidence of detectable biological 'effects', international authorities have been recommending more stringent exposure levels. As a consequence, the areas around broadcast antennas to which a person can safely gain access are becoming increasingly restricted.

This Report briefly examines the published data on biological effects and outlines the rationale behind the UK National Radiological Protection Board's new exposure guidelines. The typical field strengths around Broadcast antennas are discussed so that the operational implications can be assessed.

To ensure compliance with any recommended exposure guidelines in normal operations at broadcast transmitter sites, the fields around broadcast antennas have to be measured, at least in all access areas. This can be very difficult as the exposure environment is complex and the exposed person will nearly always be in the near-field of the transmitting antenna. Two new field strength meter designs are outlined in this Report which may help alleviate this problem. However, a large amount of development work still needs to be done before either design can be realised in a useful operational form.

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1. INTRODUCTION

Electromagnetic fields have been used for many applications over many years and until recently there were relatively few concerns over its possible health effects. However, some new results from experiments on the biological effects of non-ionising radiation have suggested that unnecessary exposures should be avoided and occupational exposures should be limited. Various international and national regulatory bodies have followed this with guidelines on the levels of electromagnetic fields to which a person can safely be exposed.

Since 1964, the BBC has worked to safety* guidelines based on Ministry of Defence advice without any obvious problems emerging. However, the new guidelines issued by the international bodies dealing with this problem are considerably more stringent and will have serious operational implications.

There is now a great deal more public awareness about this problem, particularly in the USA, which is heightened by articles in the popular press (and indeed the BBC's 'Panorama' programme on 21st March 1988) linking the fields with an increased risk of cancer. Exposure guidelines have been consistently reduced over the last few years and the Americans are currently discussing a new standard which may be even lower than the current British advice.

Exposure regulations affect BBC operations because a great deal of installation and maintenance work is carried out on antennas and their supporting structures each year. To switch off every time access to any part of the mast or antenna field is required would lead to a very large amount of programme down-time. For instance, painting a large tower structure takes around 6 weeks. BBC masts also carry a wide range of other services such as telemetry links and communications services which may not be switched off easily. Broadcasters have to achieve a compromise where areas of hazardous field strengths are outlined and cannot be entered into without the transmitter power being suitably reduced, but access to other areas on the mast is not restricted unnecessarily.

Some of the common suggestions for solving our problems include building secondary masts at every site, working at night or reducing the amount of maintenance carried out. Obviously, building secondary masts would involve a tremendous amount of construction work, which at heights, carries a very high risk factor. All work on masts is potentially hazardous — to suggest working on floodlit masts exacerbates the problem. In any case many services now operate on a 24 hour basis. In addition, any reduction in maintenance will increase the risk of antennas or masts becoming structurally dangerous. Therefore essential maintenance has to be carried out on a routine basis, while supporting a broadcast service but abiding by the exposure regulations. The decisions being made are not just economic ones but must involve balancing the different safety factors.

This Report is a review and update on the current situation regarding the reported health effects of electromagnetic fields and the new exposure standards. Typical field strengths around transmitting antennas are discussed so that the possible operational implications of limiting exposures can be assessed. The practical problems of measuring the fields will also be considered and some possible solutions suggested.

2. AUTHORITIES INVOLVED

There are a number of international authorities concerned with the health aspects of electromagnetic fields.

ANSI is the American National Standards Institute. The members of ANSI Working Group C.95 carry out a significant amount of the research work in this area. They have historically taken the lead in this field and although other authorities may make minor modifications, exposure standards in the West are generally very similar to ANSI's levels[1]. As ANSI's last standard was published in 1982, the sub-group C.95 are discussing a new proposal which is currently being re-drafted following comments received from various international experts. It will then be submitted to the board of ANSI and then to the IEEE. If approved it will be issued as the new American standard, but this process is likely to take a year or so.

IRPA are the International Radiation Protection Authority who have a sub-group INIRC (International Non-Ionising Radiation Committee). They are an advisory group of international experts in the field and their output is important since they report to the EC

* In this Report, unless otherwise qualified, the use of the words 'safe' or 'safety' relate only to the question of RF electromagnetic hazards.

on radiation matters. Based on the Environmental Health Criteria of the World Health Organisation, INIRC recommends guidelines on exposure limits, drafts codes of safe practice and works in conjunction with other international organisations to promote safety and standardisation in the field of electromagnetic radiation. They were instrumental in the adoption of a worldwide exposure standard for ionising radiation and they are anxious to do the same with non-ionising radiation. In the past they have, to a certain extent, followed ANSI's lead in this field. They published their latest proposals after considering all the evidence of biological effects to date[2,3].

In the UK, the National Radiological Protection Board (NRPB) have recently published their guidelines on the exposure to electromagnetic fields[4] (May 1989). The exposure levels adopted by them as 'reference levels' are very similar to IRPA's exposure 'limits'. However, it is the Health and Safety Commission who will decide whether or not to accept the NRPB's guidelines and to issue health and safety regulations covering this subject.

No EC directive is expected on this subject for at least 5 years because of inconclusive evidence of harmful effects.

The main scientific body promoting the relevant research work is the Bioelectromagnetics Society (BEMS), whose members are involved in all aspects of electromagnetic fields from measurements to bio-physics research. Although BEMS is currently based in the USA, the European Bioelectromagnetics Association (EBEA) has recently started which should become a very useful forum for discussion and possibly for initiating some collaborative research projects in Europe.

3. BIOLOGICAL EFFECTS

It is not within the scope of this Report to explain the biological effects of electromagnetic energy and no research work is being carried out in this area by the BBC. Indeed there have been many excellent reviews written[5-12] which serve as further references for the vast amount of literature published on this subject. It is appropriate, however, to give a brief review of the possible health effects considered by the standards authorities when setting exposure levels.

The biological effects can be categorised into three classes; radio-frequency shocks and burns, thermal effects, caused by heating of the body, and athermal effects, where there is a direct interaction mechanism between the electromagnetic fields and biological tissue.

3.1 Radio-frequency shocks and burns

Radio-frequency shocks and burns are an indirect hazard of electromagnetic fields caused by currents flowing through the body to ground. They can occur if a grounded person touches a large ungrounded object which has a charge induced on it by the field, or if an ungrounded person exposed to a field touches a grounded object. The discharge current through the body can cause a shock or burn depending on the area of contact.

The short circuit currents to ground have been investigated by a number of researchers[13-16]. For a person touching an ungrounded object with a charge induced on it, the current will depend on how well the person is grounded. For instance, rubber-soled shoes on a dry ground give a tenfold reduction in current compared to the condition where the person is barefoot on a wet surface. The current required to cause a burn will depend on the contact area and the frequency.

The perception of a contact current depends on the frequency and ranges from a tingling or prickling sensation below 100 kHz to a sensation of warmth above. The threshold for perception varies (for men) from about 4 mA at 10 kHz to 44 mA at 100 kHz and 64 mA at 200 kHz for finger contact. The threshold at 10 kHz increases to 12 mA when holding the copper wire in the hand. Painful, severe shocks are defined in terms of the let-go current which at 10 kHz is around 75 mA for men and 50 mA for women. Above this current, muscular contractions occur and it is not possible to release the conductor. There is a considerable amount of data published on the thresholds for both effects[17] and this information is used to limit currents in exposure standards.

The charge on an ungrounded object will depend on its size and its coupling into the transmission system. It is possible to calculate the effective area of various objects such as cars, construction equipment and wires (such as fences and stays). For a known effective area in a known electric field, the continuous short circuit current can be calculated. This current may be discharged through the body and causes heating, mainly in the hand, wrist and ankle. The amount of heating is determined from the conductivity data of the body, and can be significant.

3.2 Thermal effects

It is well known that the absorption of RF energy leads to heating of tissue, as in a microwave oven. The amount of heating depends on the amount of energy absorbed and the body's thermoregulatory

system. The energy absorbed, in turn, depends on the power of the source and the coupling coefficient into the body. Electromagnetically induced heating is quite different from other thermal interactions because there is a spatial distribution of the energy and very rapid rates of energy absorption can occur. Thermal interactions may result in local or whole-body temperature increases, but they may also cause biological effects without a corresponding temperature rise, due to the loading placed on the thermoregulatory system. This is commonly known as 'heat stress' and manifests itself as an increase in various hormones (such as triglycerides) which are known to be related to stress.

If the thermoregulatory system becomes overloaded, the core temperature of the body begins to rise. For core temperatures greater than 1° or 2° above normal animals show an inability to concentrate and to perform learned tasks. This is obviously a potential hazard.

A comprehensive review of thermal effects can be found elsewhere[18,19,20] and only a brief summary is given here.

Exposures which produce temperatures in excess 45 °C cause cell death in biological tissue (irreversible denaturation of proteins). However, the damage done to tissue by heat depends on both the temperature achieved and the duration of the exposure. Prolonged exposure giving a temperature rising to 41.6 °C will also eventually cause cell death. Birth defects in rats have been caused by maternal core temperature increases to around 41 °C and the same sort of exposure causes temporary male sterility. Behavioural changes in monkeys are associated with core temperature increases of greater than 1 °C[21] which is almost certainly an indication of 'heat stress'. Studies showing cancer promotion in mice at high exposures have results very similar to those produced by chronic stress.

Exposures are classified by the amount of heating produced in the body which is directly related to the power absorbed. This is known as the Specific Absorption Rate (SAR) which is the power (in watts) deposited per kilogram of tissue. However, the biological effect of a given SAR will depend on the thermoregulatory system of the animal being exposed; humans, in particular, have a very efficient thermoregulatory system. There is also a frequency scaling effect due to resonant absorption which depends on the animals size, and the effective penetration depth which depends only on the tissue type. Therefore microwave radiation at 2.45 GHz with a penetration of around 2.5 cm will heat a small rat or mouse to the core but will obviously not have the same effect on a human.

Additional biological effects in animals are alterations of neurons in the central nervous system at an SAR of 2 W/kg (in animals), changes in the endocrine system and hematologic and immunologic systems and alterations in brain activity[22,23,24] at SARs of around 1 W/kg. Many of these effects are reversible in that they revert to normal operation when the exposure is ceased. However, one serious thermal effect occurs in the eye. Here permanent damage can occur if the eye experiences SARs of 1 to 4 W/kg[25,26] as the eye has no internal cooling mechanism.

Based on these animal experiments, the threshold for hazardous thermal effects is associated with a specific absorption rate of 4 W/kg but thermal effects do occur at lower SARs, which although not clearly detrimental, may be considered undesirable.

3.3 Athermal effects

Recently a number of papers have been published which claim that electromagnetic fields can interact directly with tissue rather than via a heating effect[19,27]. These 'athermal' effects were not originally thought to exist since the energy in a photon of microwave radiation is 1/6000th that of ionising radiation and not strong enough to break even the weakest chemical bonds. However, researchers have found a number of biological effects which are not easily explained.

The suggested link with cancer promotion is probably the most well known of these athermal effects. Many papers have claimed a link between very low-level magnetic fields and leukemia, in particular the Savitz study claimed that magnetic field strengths in homes near high voltage power lines correlated with an increased risk of childhood leukemia[28]. This is supported by experimental evidence of cancer promotion in human cells[29,30], but other studies have failed to find any effects[31]. An epidemiological study recently carried out in south London[32] showed some increased risk of leukemia in people living near electricity transmission and distribution equipment, but it was found to be not statistically significant. However, a study of New York telephone linemen[33] did show statistically significant elevated risks of cancer which have yet to be explained.

This argument has been further complicated by recent results suggesting that there is an increased risk of cancer associated with exposure to electromagnetic fields at particular field strengths, but no increased risk at *higher* field strengths[34]. Some have even used radio-frequency radiation to inhibit the growth of cancer cells[35].

Although most of these studies concentrate on low frequency fields, there is much evidence to suggest that higher frequency fields which are deeply amplitude modulated by lower frequencies will produce an identical effect.

Another athermal effect which has repeatedly been reported relates to the movement of calcium ions under the influence of magnetic fields[36,37,38]. Calcium ions are essential for the operation of every cell in the human body and are transported across cell membranes as part of the cell's communication process. A theory has been put forward to explain this effect, called calcium cyclotron resonance[39] but other researchers have failed to replicate this work[40]. The health effect on humans is largely unknown but the calcuim ion balance is restored when the exposure ceases. For this reason, whatever the effect may be, it is thought to be reversible.

It has been postulated that magnetic fields affect circadian rhythms via an interaction with the pineal gland in the brain. The pineal gland triggers neurotransmitters which control melatonin levels, which should remain low during the day and increase after dark. Exposures to magnetic fields can lead to circadian rhythm dyschronism which is itself linked to depressive disorders[41,42]. This may sound fairly unlikely but recent work has shown that some animals do detect magnetic and electric fields[43] and it is possible that there may be receptors in the human brain.

Although there appears to be a multitude of unpleasant effects, it is important not to under-estimate the number of experiments which have been carried out in this field which have yielded 'negative' results[44]. Many of these studies are not published as often the onus is on research teams to publish only 'positive' results. Negative results from organisations seen to have a vested interest, such as the EPRI (Electric Power Research Institute), are looked upon with some scepticism by one part of the scientific community. But other, apparently neutral, workers may be under pressure to publish positive results in order to retain their research funding.

Many of the reported athermal effects are specific to the modulation, frequency, intensity and exposure system. The interaction mechanisms have not been established and any health implications are unknown. Furthermore, the identification of a biological 'effect' does not necessarily imply a condition hazardous to health. For these reasons athermal effects have not, so far, been included in standards setting. If, in future, they prove to represent a quantifiable hazard, they will then be considered.

3.4 Epidemiological studies

It might be hoped that any possible interaction of electromagnetic fields with the human body would manifest itself in health effects which would be picked up in epidemiological studies. Unfortunately, this is not the case. A review of epidemiological studies[45] indicates that their conclusions are highly controversial. There is a problem in assessing actual exposures and in selecting an appropriate control group. There may also be other contributing environmental factors which cannot be effectively controlled and some studies rely on subjective complaints such as 'tiredness' or 'depression' as end-points.

To date, epidemiological studies have not been able to adequately confirm, or deny, the existence of hazardous health effects from continuous low-level exposure to electromagnetic fields. However, such studies are considered by many people to be a very important factor in the risk analysis of exposure standards and there are plans for more controlled analyses to be performed in the future. A list of current epidemiological studies being undertaken by various groups is given in Microwave News (Nov/Dec 1989).

4. EXPOSURE STANDARDS

To clear up one point that is often misunderstood, restrictions on electromagnetic fields are classified as emission standards or exposure guidelines. Emission standards cover unwanted radiation from devices such as VDUs and digital equipment and usually specify very stringent levels which have to be met to avoid electromagnetic interference to other users of the radio spectrum. These are mainly of concern to equipment manufacturers and recommendations have recently been issued by an EC working group.

Exposure standards, however, relate to the exposure of people to radio-frequency radiating devices, such as broadcast antennas and telecommunications equipment. Such devices are intended to emit energy so it would not be appropriate to apply emission standards to them! Instead exposure standards have to be formulated which relate to a safe level of radio-frequency energy which can be absorbed by a human without any deleterious health effects. Such exposure standards have not yet been set in any country except Sweden. However, many authorities have issued 'recommended levels' and most organisations find it politically unacceptable to adopt working practices which continuously or flagrantly exceed these values.

4.1 Rationale for the NRPB guidance

A rationale has been developed over the years for producing safe exposure levels based on known

biological effects[46,47,48]. The levels adopted are basically calculated to prevent thermal effects in a body and also to prevent radio-frequency shocks and burns. However, there are additional restrictions on the amount of current that is allowed to flow through the body so that endogenous or natural body currents are not exceeded.

Normally when safety regulations are drafted, the starting point is a data base of adverse effects and a prediction of the interaction mechanisms. A quantitative analysis of the health risks associated with any proposed safety level can then be carried out. It is also desirable to carry out a cost/benefit analysis. However, this is not the case for the exposure limitations for electromagnetic fields. There are very few health effects on humans and, so far, epidemiological surveys have been very poorly controlled. Therefore most standards authorities admit to there being 'insufficient evidence to make a hazard assessment'[2].

Instead, exposure guidelines are based on the results of animal experiments, with rather complex scaling mechanisms to apply the same exposure criteria to humans. Obviously humans have a completely different physiology from laboratory animals and it is often difficult to relate experimental results to hazards to human health. Thus the rationale behind many exposure standards is necessarily subjective both in consideration of the experimental results themselves and their health implications. The following sections outline the reasoning behind the NRPB's guidelines, but in many instances the same rationale is used by ANSI, IRPA and other standards authorities. The exposures relating to pulsed fields has been omitted as it is not of direct relevance to broadcasters.

4.1.1 Recommended current limits

At lower frequencies, below 30 MHz, there are restrictions placed on the currents flowing in the body. This is a useful approach from a standards setting point-of-view as it allows the induced currents to be compared with those which would produce physiological responses (such as muscle stimulation) and they can be compared to the endogenous body currents. Body currents will also give an indication of the possibility of radio-frequency heating occurring in limbs if the exposed person touches a grounded metal object.

The NRPB advice is given in the Appendix, Table 4. The continuous electric current induced in any arm or leg either directly by the electromagnetic field or from contact with an object, should not exceed:

$$[1 + f(\mathrm{Hz})/1500]\ \mathrm{mA}\ \text{or}\ 100\ \mathrm{mA},$$

whichever is the smaller for $f < 30$ MHz.

At low frequencies this current limit is a factor of five below the 'let-go' current even for the most sensitive individuals and children. At higher frequencies in the specified range, the 100 mA current limit will prevent radio-frequency burns in most cases. Only on point contact, could 100 mA cause a burn and then the small area involved reduces the seriousness of the hazard.

If a grounded person touches a large ungrounded conductor which has a charge induced on it by an electric field, high transient currents will flow and an RF burn may result. Such RF burns and shocks are fairly common at MF and HF transmitting stations. The NRPB advice on this matter is that "radio frequency burns from contact with objects in the electromagnetic field should be avoided". Since the field strength that would cause a burn depends on the size of the object and its coupling into the field, it is not possible to simply limit the field strengths allowed. In most cases, RF burns can be avoided by appropriate operational practices.

4.1.2 Whole body SAR

Consideration of thermal effects has led to a whole body average level of power deposition of 4 watts per kilogram of body weight to be used as the threshold for thermal effects. A specific absorption rate of 4 W/kg results in 280 W total in 'standard man' with a weight of 70 kg. This threshold can also be considered from the point of view of the normal human metabolic rate. A heat production of between 250 to 1500 W is normal in a healthy human, depending on factors such as exercise. Therefore an incident electromagnetic field depositing an average of 4 W/kg in the whole body is not producing an excessive load on the thermoregulatory system. However, this does not take into account other ambient heating or cooling effects.

Exposures are averaged over a six minute (0.1 hr) period to allow for the thermal time constant of the body. This applies to all exposure limits based on heating, either of the whole-body or of part of the body.

A safety factor of 10 is applied to the SAR threshold to give an exposure limit of 0.4 W/kg averaged over the whole body (or 28 W total in 'standard man'). Most authorities now use a whole-body average SAR of 0.4 W/kg as the limit for safe exposure and there is pressure for further reductions based mainly on the possible existence of athermal effects.

4.1.3 Localised SAR

In addition to a whole body average limit, the localised SAR in any 0.1 kg of tissue is limited to

prevent local heating. An SAR of 20 W/kg in any hand, arm, leg or foot and 10 W/kg in any internal organ is considered safe. This compares to typically 40 W/kg if a hand is placed in warm water. Results from patients undergoing diathermy treatment suggests that there is no harmful effect on health from such localised heating. It is well known that working in a radio-frequency field can cause heating in the wrists and ankles due to the continuous flow of currents to ground and care should be taken to ensure these localised heating limits are not exceeded[49].

4.1.4 Other considerations

The NRPB and IRPA do not take athermal effects into account when setting exposure levels. In their guidance document[4], the NRPB state that 'at present there is insufficient data either to make a health risk assessment or even to determine whether there is a potential hazard to health with regard to the possible (athermal) effects'. However, they reserve the right to change their mind if other evidence becomes available.

4.2 Derived field strengths

The difficulty with the concept of a specific absorption rate (SAR) is that although it relates to biological effects it is totally impracticable to measure in practice. As soon as a thermal load is applied to the human body, the thermoregulatory system begins its cooling processes. Therefore, to allow the SAR limits of Table 4 in the Appendix to be applied in exposure situations, 'derived' levels have to be evaluated which are the field strengths which would not exceed the SAR limit, even under maximum coupling conditions.

To determine the amount of energy absorbed by a body in the presence of an RF field, measurements of SAR have been done on human models (phantoms) which are exposed to a known incident field and the resulting temperature rise measured. The results from animal experiments can be extrapolated to human sizes although it is not a simple frequency scaling process but depends also on penetration depth. Modelling work is used to fill the gaps in the experimental data[50,51]. At low frequencies the body absorbs very little of the incident field but the coupling increases until resonance occurs at about 30 MHz for standard man on a perfect ground plane. This results in the largest whole body SAR level for a given incident power density; at this point the body will absorb 3.5 times its physical aperture. However, these calculations are performed assuming worst-case coupling conditions, that is, the exposed subject is standing barefoot, on a perfectly conducting ground plane and on one leg!

Towards the higher frequencies the coupling coefficient decreases again and asymptotes to a value where roughly half the energy incident on the physical aperture is absorbed and half is reflected or scattered.

The resonant frequency obviously depends on the size of the person and whether the coupling conditions approximate to a quarter-wave monopole on a ground plane, or a half-wave dipole in space. Part-body resonances also exist, for instance there is a resonance of the head at around 340 MHz[52]. The SAR achieved for a given incident power density for a variety of conditions is shown in Fig. 1.

Constructing an envelope around these various absorption characteristics will include all the incident power densities that can produce a specified SAR at each frequency. Inverting this characteristic gives incident field levels to which a person can be exposed without exceeding a specified SAR even for worst-case absorption. This envelope then becomes the basis for an exposure standard.

Fig. 2 shows the current exposure levels recommended by the NRPB, IRPA and ANSI at the time of writing, but they may change in the future. The scales show *E*-field values and power density as these are normally used to measure the fields. A table giving the recommended field strengths can be found in Table 5 of the Appendix which is taken from the NRPB's guidance document[4].

It can be seen that the low coupling at low frequencies results in high derived field strengths before the SAR of 0.4 W/kg condition is approached. The field strengths do not continue to rise, however, because of the additional hazard of RF shocks and burns. The field is limited to prevent a severe shock if a grounded person touches a large ungrounded object, such as a van or bus. The exposure levels have a 'well' in the body resonance region (roughly 10 MHz to 1 GHz) corresponding to the maximum coupling range, and then a constant level at higher frequencies where the body can be modelled as an absorber. Above 1 GHz, about half the power density incident on the physical aperture of the body is absorbed, and the other half is reflected.

The *E* field (in V/m) and *H* field (in A/m) values are calculated assuming far-field plane-wave exposure conditions. Obviously, in practice, the nature of broadcasting is such that the most significant field strengths, and hence the possiblity of a hazardous exposure, are in the near-field of the source. This means that these derived field strengths are not a good indication of SAR and therefore the possible hazard. Additionally the way in which the derived values are calculated applies extra safety factors over the basic

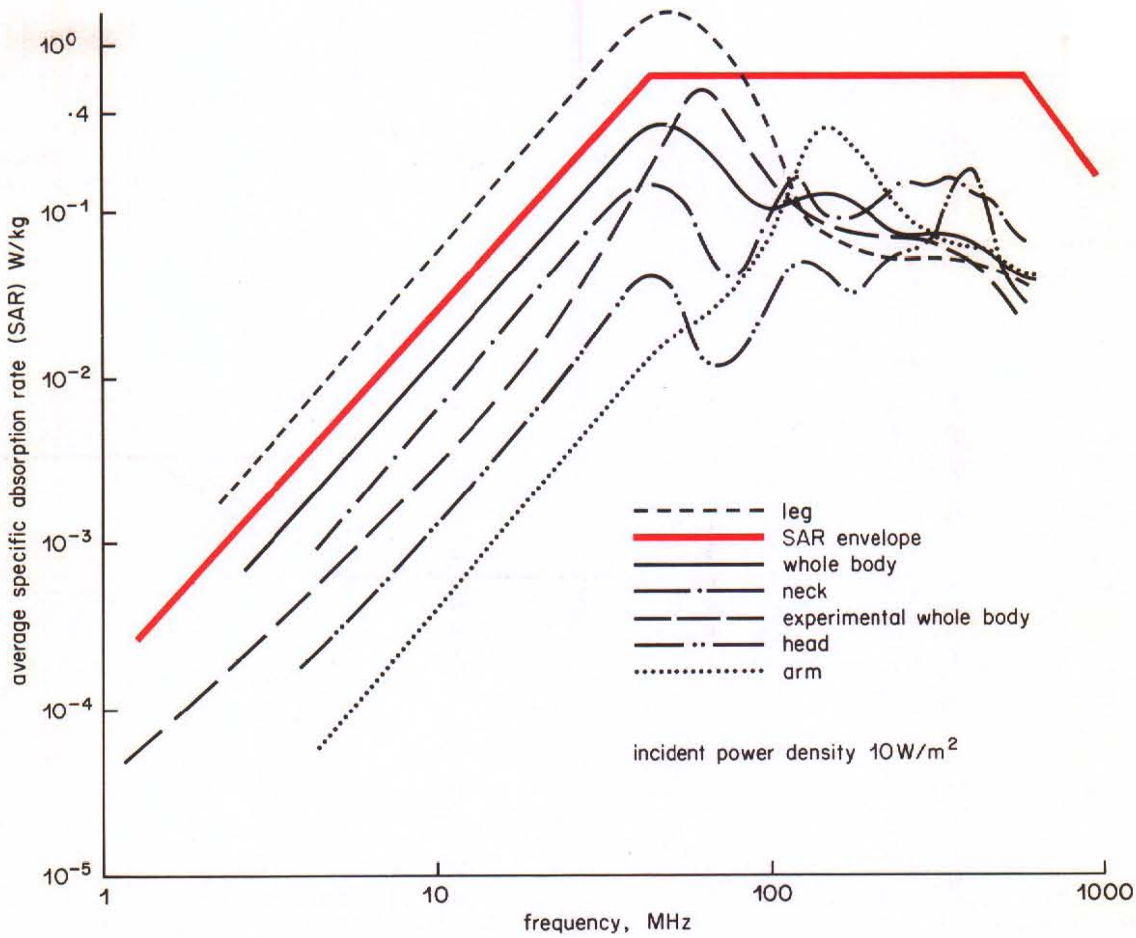

Fig. 1 - Specific Energy Absorbed for a given incident field.

SAR restriction. The NRPB recognises this problem and in Paragraph 12 of their Guidance document[4] they offer to provide 'specific advice' on compliance with the limits of Table 4 in the Appendix, rather than the derived field strengths of Table 5.

4.3 Public exposure levels

Here there is a difference in the rationales of the international body IRPA and the UK's NRPB. IRPA recommends that the basic SAR limit should be reduced by a factor of 5 for public exposure on the grounds that they may be exposed 24 hours a day, they are an uncontrolled population (of varying health, age etc.) and they cannot be expected to take precautions to avoid radio-frequency shocks and burns. The NRPB, however, states that a number of safety factors are already included in the exposure rationale and the Board is 'unable to find any scientific justification or need for further safety factors of any particular magnitude'. They do agree with IRPA about the problem of the possibility of radio-frequency shocks and burns, and the public will be protected by a reduction in the recommended electric field by a factor of 3 for frequencies below 30 MHz. This will prevent a shock or burn if a child touches an ungrounded object such as a van or bus in the field.

4.4 Exclusions

In general, low power devices of output power of less than 7 W are excluded from compliance with the derived reference levels. However, the NRPB feel that the manufacturers of such devices should ensure that they do not exceed the basic SAR or current limitations particularly if the eyes are exposed.

5. MEASUREMENTS OF FIELD STRENGTHS AND OPERATIONAL IMPLICATIONS

Although very few countries have 'exposure standards' as yet, most European Broadcasters are now being faced with exposure 'guidelines' from international and national bodies. It would be unacceptable to ignore these guidelines, so the typical field strengths at broadcast sites have to be measured to assess the operational implications of complying with the new exposure guidelines.

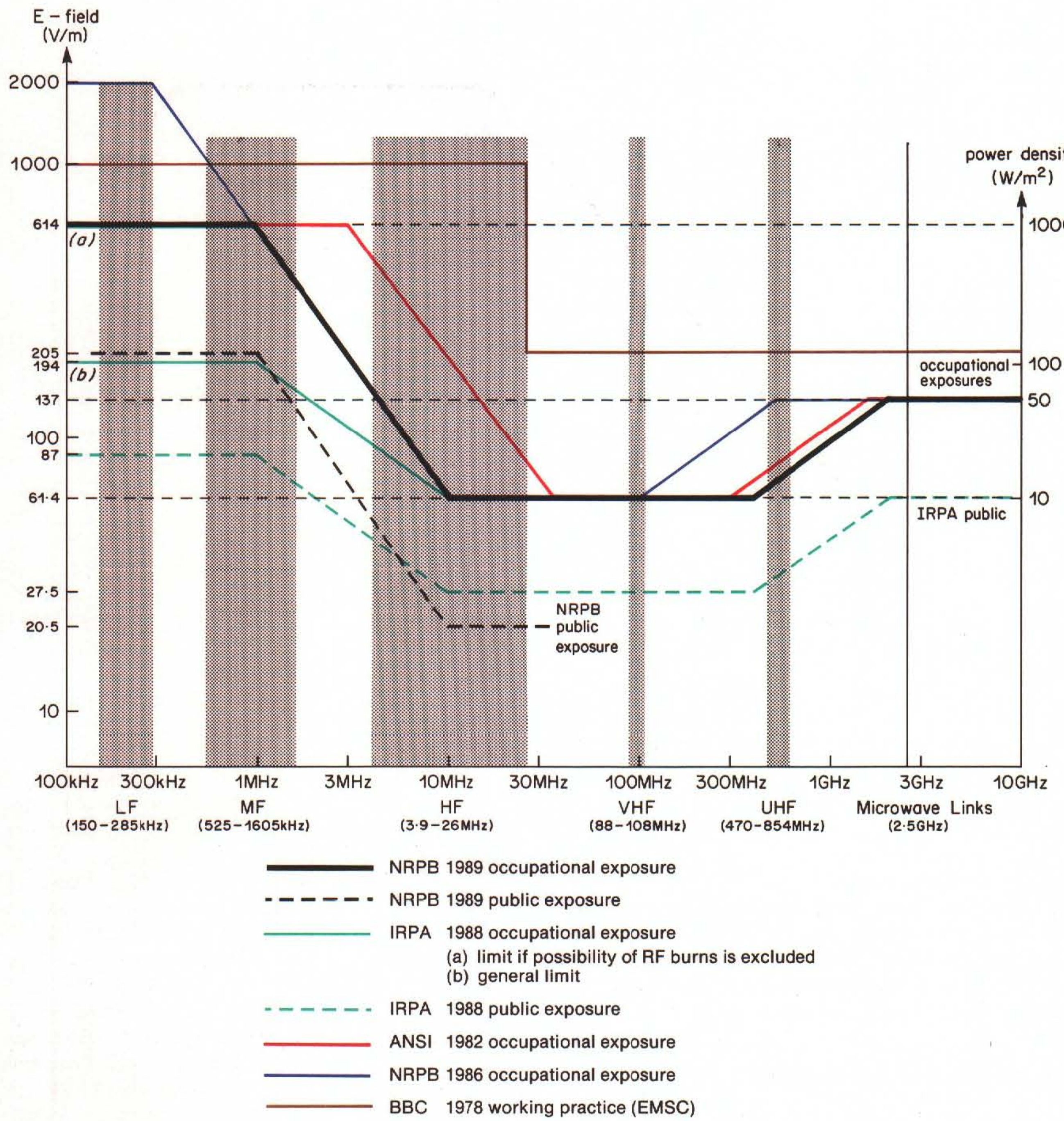

Fig. 2 - Current exposure guidelines covering broadcast bands.

At present, there is no practical method for measuring SARs, so *E*-field measurements are made and compared with the derived field strength reference levels. However, making valid measurements in the near-field of transmitting antennas is often difficult. There are several problems to be considered. Firstly, the person making the measurements will actually alter the field present, so there is the question of the validity of the measurements; should the exposure be assessed using the field when the person is absent, or when they are present? Secondly, there is sometimes a large spatial fluctuation of the field and in these cases it is only possible to make a rough estimation of the general field strength levels. The large amount of metalwork present results in complex reflections and perturbations of the field.

To make comparisons with the recommended exposure levels, the field should be measured over 6 minutes and then an average taken. This result would obviously depend on the exposed persons movements within the field and requires a fairly sophisticated meter.

Most commercial field strength meters detect one component of the field only and convert it to the

equivalent far-field power density. This can lead to very large errors in the near-field and the specification of many measuring instruments (such as the Narda and Raham meters) excludes their use in the near-field. They are quoted to give readings accurate to within 2.5 dB, but tests have shown that in certain situations the readings can be in error by very much more than this.

In the reactive near-field of a transmitting antenna, the power in the field oscillates between the E and H components and it is the Poynting vector, taken over a closed surface, which gives a true value for the power available in the field. It is not possible to draw power out of a reactive field, so measured E-field values would suggest a higher SAR in the exposed person than would actually be possible. To date, however, commercial meters which can detect the time-phase between the E and H components of the field and give a true value for the power density are not available.

In the following discussion, measurements taken with meters which indicate power density are converted back to E-field values, when E-field probes have been used, to avoid at least one incorrect assumption.

Broadcasters now face reduced exposure levels from HF to UHF. The new recommended E-field strength is as low as 61.4 V/m for some frequencies, (c.f. the BBC had for many years operated within 200 V/m at VHF and UHF, and 1 kV/m at HF). E-field values have always been considered because, so far, they are the only quantity that can be measured easily. It is also worth remembering that the NRPB also set public exposure levels below 30 MHz which are one third of the field strengths for occupational exposure.

5.1 SHF

For a microwave antenna, the field strengths in front of a dish can be calculated fairly easily and an exclusion zone is set up around it. There have been no great difficulties with this system and the boundaries are easily checked on site by measurement. Currently, microwave devices are checked against the 50 W/m^2 (5 mW/cm^2) power density reference levels. Interlocking devices are also used to prevent antennas on elevating masts from transmitting in the down position.

However, each time the allowed exposure level is reduced, the exclusion zone has to be increased and more of the low power devices have to be checked to ensure that the transmitted power density does not exceed the reference level in any area where there may be human exposure. Increasingly this problem will have to be considered when the equipment is designed, both for occupational and public exposure.

5.2 LF, MF and HF

The field strengths around low and medium frequency masts and HF arrays can also be calculated, although not so easily confirmed by measurements. At MF and LF the allowed field strengths are high and only exceeded very close to the antennas. However, access to the mast itself while it is transmitting is now difficult as the measured E field on a mast radiator will usually exceed the derived field strengths allowed (614 V/m).

However, as noted in the discussion on the rationale for these reference levels, the derived levels are set to prevent shocks and burns. In the environment of a mast there is no way that an operator can receive a shock as there is no path to ground, except at the time of access to the mast, when the power would be switched off and the mast grounded. Thus a higher figure would be more appropriate to guard against body currents as this is the main hazard to the person. This explains why there have been few problems when masts were painted whilst transmitting for example.

At HF stations, measurements suggest that large areas of the antenna field around high-power transmitting arrays will exceed the derived E-field value, especially near open wire feeders. Many of these are now being encased by trunking to reduce the field but little can be done around the arrays themselves. Therefore, parts of the antenna field which exceed 61.4 V/m will become exclusion areas and maintenance schedules have to be planned to avoid times when the array is transmitting[53,54]. However, with field patterns changing every 15 minutes at some HF sites, most of the antenna field becomes an exclusion zone!

5.3 VHF and UHF

Probably the biggest problem area so far arises on high-power VHF and UHF masts[55]. It has not proved possible to calculate the fields on masts so far because of the large amount of surrounding metalwork. Therefore, to get an estimate the typical field strengths near our transmitting antennas, they have to be measured. This in itself is no trivial task.

At high-power sites, the E field near the UHF panels and often on the working platform below it will exceed the allowed exposure levels. However, these fields are fairly well-behaved and local to the UHF panels, decreasing rapidly with the distance from

the bottom antennas. Currently, no work is carried out on or near high-power UHF panels without the power being reduced.

At high-power transmitting stations, the VHF panels are usually placed around the mast just below the UHF antennas and the riggers have to climb through the VHF tiers to gain access to the upper working platforms. Measurements in the climbing space behind the VHF panels are not straightforward, see Fig. 3. The large amount of surrounding metalwork leads to very high *E*-field readings due to re-radiation from the reflector mesh and the mast structure itself. Also, local 'hot-spots' are evident which can give field strength readings up to an order of magnitude higher than the average readings in the climbing space.

In addition to these problems, the wavelength at VHF is around 3 m so the inside of the mast acts as a waveguide and standing wave patterns are set up. Although the presence of the person making the measurements in the climbing area disturbs the field, these variations can still be detected. Therefore we end up comparing *E*-field readings taken in a highly complex exposure environment with derived field strength limits which are themselves very dubiously related to SAR.

The field strengths behind the VHF tiers have been measured at a number of high-power sites, and the results indicated that the *E* field generally varied from 43 to 137 V/m in the climbing space but small 'hot-spots' exceeded the full scale deflection of the meter at 275 V/m. Field strengths on the working platform below the VHF tiers were consistantly less than 61.4 V/m and below this the field attenuates very rapidly.

These readings suggest that climbing through and passing in front of high-power VHF antennas will have to be restricted. However, this is based on *E*-field readings only which include reactive field components, particularly in 'hot-spot' areas. The power available in the field will tend to be over-estimated and there is no direct relationship to SAR and hence the possible hazard. However, based on these measurements, access to all the upper working areas on a mast may be limited.

The BBC is currently working in collaboration with the NRPB in an attempt to make more meaningful measurements. Body current measurements may give a greater insight into the amount of power coupled into the body when inside a mast structure. Also a data logging device may be used to perform some measurements over the six minute averaging period. This will help to identify the restrictions on operational practice required.

6. FIELD STRENGTH METERS

The measurements of Section 5 indicate that the field strengths present around typical BBC transmitting antennas are of the same order of magnitude as the recommended exposure levels. Therefore, inaccuracies in the readings and incorrect assumptions do have very significant effects on

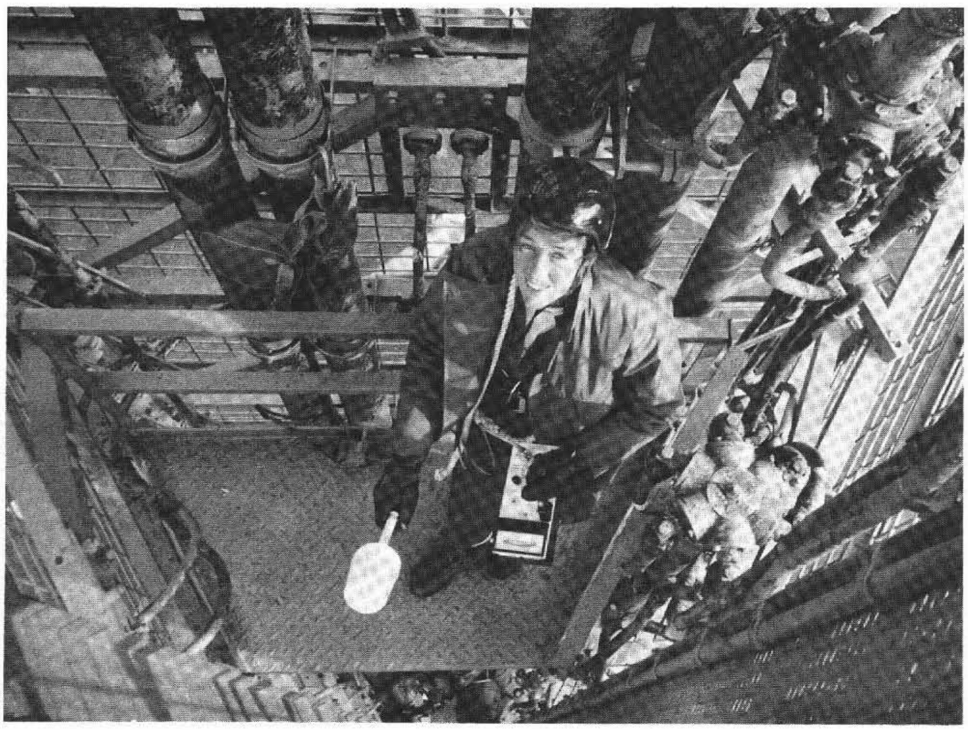

Fig. 3 - Practical aspects of measuring the electric field strengths in the climbing space behind the VHF stack at Wenvoe.

working practices. It would help if we could at least measure the actual power available in the field rather than working with just the E or H component. Two new field strength meters based on this assumption have been considered by the BBC; one based on thermal principles and the other on the interaction of the field with optical sensors.

6.1 The thermal meter

One way of detecting the power available in the field is to absorb the electromagnetic energy in a piece of material and to measure the resulting temperature rise. This is not as simple as it sounds because the derived power density may be as low as 10 W/m^2 (1 mW/cm^2) and this has to be converted to a measurable temperature rise, possibly in the presence of sunlight at 1000 W/m^2 (100 mW/cm^2) or a cooling wind.

There are a number of things to be considered. Firstly the impedance of the material must be well matched to free-space or most of the incident energy will be reflected. Then there must be a loss mechanism in the material which converts the field components into heat. Finally the resulting, extremely small, temperature rise has to be measured and calibrated to relate to the incident power density. For the small power density allowed at VHF, the resulting temperature rise will be of the order of 10^{-5} °C which may be beyond present day measurement capabilities.

An experimental field strength meter has been designed and constructed by the BBC along these lines and operates satisfactorily at 12 GHz. An outline of the meter is shown in Fig. 4. It has two temperature sensing heads, one of which is covered in microwave absorbing material. The heads are thermally insulated from each other and the outside world and the temperature difference between them can be related to the incident field.

At microwave frequencies it is possible to use quarter-wave resonant absorbers with excellent absorption characteristics for a thin piece of material. A similar absorber at VHF wavelengths would be far too large to heat up in such a low incident field. Ferrite absorbers can be made with specified values for the complex permeability and complex permittivity such that the ratio of the two is matched to free-space, allowing the field to be absorbed in a small quantity of material. However, such ferrites are extremely complex to design and are not yet readily available.

The experimental meter currently has the disadvantage that to allow calibration, the measurement must start with the probe head at ambient temperature so it has to cool in a zero field environment between each reading. This problem would have to be solved if this design was extended to lower operational frequencies for use on transmitter masts.

6.2 The optical meter

An alternative method for detecting the power available in the incident field is to obtain a measure for the Poynting vector ($E \times H$). This can be achieved by measuring the E and H field in three orthogonal planes and multiplying the components together. It is possible to detect both fields and perform the multiplication optically using field sensitive optical crystals. There are several methods of interaction between electromagnetic fields and optical crystals but two of the most useful are Pockel's effect and Faraday rotation which can both be linear with respect to the applied fields. The difficulty with this design is that the polarisation rotations to be measured are very small, just because the field strengths to be detected are low and the electro-optic and magneto-optic constants are small. However, future materials may provide a larger effect which would make this design a very attractive proposition. Care also has to be taken to avoid optical

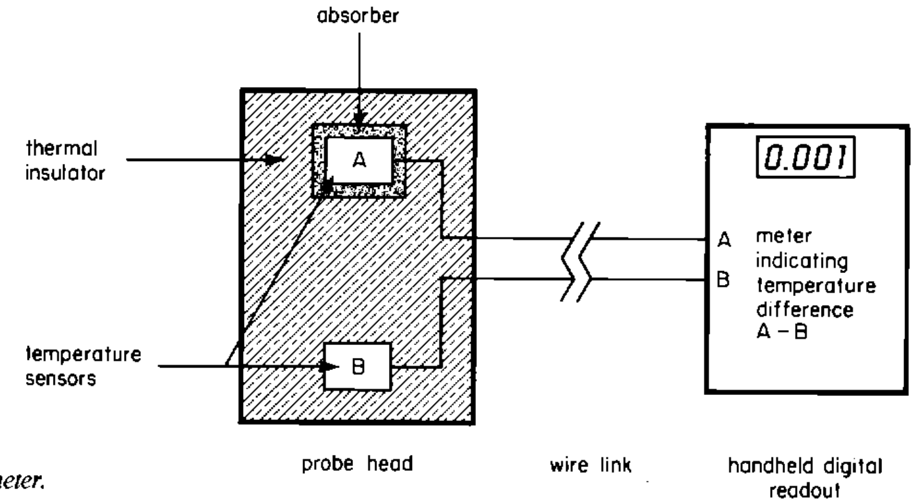

Fig. 4
An experimental thermal field strength meter.

resonance effects which would prevent calibration of the meter across a broad frequency band.

It may be possible to lay out the whole design in integrated optics as work carried out in Japan has shown that the same effect can be achieved in optical waveguides on garnet substrates. This sounds very hopeful as it would lead to a very small device.

7. FUTURE WORK

Greater attention is being given to the exposure of people to electromagnetic fields. Each time guidance is reviewed, lower exposures have been proposed and it has now reached the stage where serious operational difficulties result. Obviously, levels must be set to ensure safety in the light of all the biological evidence relating to different health hazards. However, care should be taken to ensure that incorrect assumptions about the exposure environment are not causing operational difficulties unnecessarily.

To assist in complying with the basic exposure restrictions, we need to find ways of measuring or predicting the SAR deposition in a body for any incident field. This will allow us to comply with the basic restrictions given in the Appendix, rather than the derived field strength values which may apply additional unecessary restrictions.

7.1 Dosimetric modelling

The SAR deposition in a body can be calculated by modelling the body as cells and giving each the electrical properties of a tissue type such as bone, fat, muscle etc. A plane wave incident on the body is propagated through the model using the finite-difference time-domain (FDTD) method. This is explained fully in Refs. 56-59 but this method requires a large amount of computer processing. It is even more difficult in near-field exposure situations and here the accuracy of the results cannot be verified easily.

7.2 Use of phantoms

An alternative to calculating the SAR deposition is to measure the heat deposited in a full size model of 'standard man', known as a phantom. This has been done in a variety of problem areas by the US Navy[60]. If the model absorbs less than 0.4 W/Kg then the field strengths can be increased. This has the advantage that it can be used in the real-life complex exposure environment but requires very high transmitter powers to produce a temperature rise which can be measured in a calorimeter. The results are then extrapolated back to the actual operating powers. This method has solved many of the US Navy's problems but would be difficult to apply to conventional broadcast antennas where high powers are already being used and the exposed area may be behind a reflector.

7.3 Improved measurements

Of primary importance is to improve the accuracy of near-field measurements. If the two meters described in Section 5 could be implemented to an operational standard, they would at least solve the problem caused by having to comply with *E*-field exposure levels rather than power density. Unfortunately, if the standards rationale is changed, possibly due to health effects becoming primarily related to one component of the field or the other, then these meter designs would be rendered useless.

Another possibility is to measure the currents flowing in the body, from which a good estimate of the SAR can be calculated. However, it is really only possible to measure the foot-to-ground, or the hand-to-ladder currents, which give no estimate of currents which may be circulating in the trunk. Thus contact current measurements will still only give approximate SAR values and such measurements are very difficult to make in the complex exposure environments which exist on masts. The NRPB have produced an experimental ankle current meter but, at present, it will not work in high VHF fields because of RF interference.

8. CONCLUSIONS

Broadcasters face a variety of problems when trying to ensure safe operational practices in areas with significant levels of electromagnetic fields, such as exist close to transmitting antennas. The exposure guidelines have become more stringent each time they have been updated and it may be that operational practices employed now will need to be periodically revised. The international authorities in this field appear to be tending towards an 'as low as reasonably achieveable' principle in the light of inconclusive biological evidence which will create more problem areas in the future. The NRPB have not made specific reference to this in their recent guidelines.

Obviously the principle of exposure limits must be upheld to ensure safety, but the safety factors are being compounded by incorrect assumptions regarding exposure conditions. The derived field strengths of exposure standards are calculated assuming optimum coupling conditions and far-field, plane-wave exposures. Whereas, in broadcasting, the potential for hazard is generally confined to the near-field around

the transmitting antenna and hence the derived field strength values are inappropriate for determining true SAR levels and hence the actual level of potential hazard.

The NRPB guidance document recognises the problems in calculating derived reference levels and in Paragraph 12 they emphasise that "*These reference levels should not be regarded as limits* and should be used to indicate a requirement for guidance as to the appropriate administrative and technical measures to limit exposure." The guidance allows the field strengths in access areas to be greater than the derived levels provided that the basic SAR limit is not exceeded. More work is needed to establish a reliable and accurate method for measuring the electromagnetic fields in the near-field environment and to determine the relationship to SAR values. The NRPB are currently giving advice to the BBC on this matter.

Two field strength meters have been proposed which may help to resolve some of the difficulties of measurement by detecting the actual power in the field rather than the E field only. However, there is still a great deal of development work to be carried out before either of these could become suitable for operational use.

This solution is acceptable while the exposure rationale is based on power deposition and power densities. Currently, under 30 MHz the exposure rationale is based on radio-frequency shocks and burns and the electric and magnetic field strengths have to be considered separately. ANSI have suggested that this break-point should be moved to 300 MHz and if the NRPB accepts this rationale, we could no longer use power density as the exposure measure at VHF.

Thus our solutions may be limited to calculating SAR depositions in block models or measuring the heat deposited in saline-filled life-size models in the actual exposure environment. These calculations are very complex for near-field exposure environments although some researchers are finding some solutions. The difficulty is that funding is very limited in this field and has, so far, tended to be concentrated on electric power frequency fields. Broadcasting organisations could usefully encourage greater research into the biological effects of higher frequency fields.

Scientific organisations such as the Bioelectromagnetics Society (BEMS) and the European Bioelectromagnetics Association (EBEA) have members involved in all aspects of the effects of electromagnetic energy from measurements to bio-physics. They provide a forum for collaboration and discussion on this subject and it is important that broadcasters are willing to become involved in such groups if they wish to be represented.

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APPENDIX

Current NRPB Guidelines

The current advice from the National Radiological Protection Board is given in their document 'Guidance as to Restrictions on Exposures to Time Varying Electromagnetic Fields and the 1988 Recommendations of the International Non-Ionizing Radiation Committee', document NRPB-GS11. Their advice is summarised in Tables 4 and 5 of this document which are reproduced below.

Table 4
Basic restrictions on exposure to electromagnetic fields at frequencies below 300 GHz advised by the Board.

Item	Restrictions
1	The continuous induced current in any arm, hand, leg, ankle or foot should not exceed: $\left[1 + \frac{f(\mathrm{Hz})}{1500}\right]$ mA or 100 mA whichever is smaller for frequency f less than 30 MHz.
2	The average specific energy absorption rate in the body over any 6 min should not exceed 0.4 W kg^{-1}.
3	When taken in conjunction with 2 above, the maximum value of the specific energy absorption rate in any 0.1 kg of an internal organ or tissue in the head or trunk over any 6 min should not exceed 10 W kg^{-1}.
4	When taken in conjunction with 2 above, the maximum value of the specific energy absorption rate in any 0.1 kg of an arm, hand, leg, ankle or foot should not exceed 20 W kg^{-1}.
5	Exposures to time integrated power densities in any pulse of duration less than 50 μs exceeding 0.4 J m^{-2} should be neither prolonged nor frequent.
6	Radiofrequency burns from objects in the field should be avoided.
7	Any uncomfortable sensation of heat in the superficial layers of the body should be avoided at frequencies above 1 GHz.

Table 5
Derived reference levels for exposure to electromagnetic fields at frequencies below 300 GHz advised by the Board

(a) For frequencies below 30 MHz: electric and magnetic fields to be separately considered.

Frequency	Root mean square values		
	Electric field strength (V m^{-1})	Magnetic field strength (A m^{-1})	Magnetic flux density* (mT)
<100 Hz	614,000/f(Hz)	1630	2
0.1-1 kHz	614/f(kHz)	163/f(kHz)	0.2/f(kHz)
1-30 kHz†	614	163	0.2
0.03-1 MHz†	614	4.89/f(MHz)	6.10^{-3}/f(MHz)
1-10 MHz†	614/f(MHz)	4.89/f(MHz)	6.10^{-3}/f(MHz)
10-30 MHz†	61.4	4.89/f(MHz)	6.10^{-3}/f(MHz)

Note: f = frequency in the units shown within brackets.

* Magnetic flux density in tissue is given as an alternative to the equivalent magnetic field strength.

† At these frequencies the reference electric field strength in uncontrolled areas of public access should be one-third of the values in the table because of the possibility of electric shock or radiofrequency burns from exceptionally large ungrounded objects in the field. See also paragraph 23.

(b) For frequencies above 30 MHz: electric field strength, magnetic field strength and power density to be taken a equivalent alternatives under far-field conditions.

Frequency	Root mean square values		
	Electric field strength (V m^{-1})	Magnetic field strength (A m^{-1})	Power density (W m^{-2})
30-400 MHz	61.4	0.163	10
0.4-2 GHz	97.1$\sqrt{f}$(GHz)	0.258$\sqrt{f}$(GHz)	25f(GHz)
2-300 GHz	137	0.364	50

Note: f = frequency in the units shown within brackets.

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